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TECHNICAL REPORT ARBRL-TR-02460

NUCLEATION THRESHOLD STRESSES FOR THE  
DYNAMIC FRACTURE OF A  
LOW-ALLOY NI-CR STEEL

Gerald L. Moss  
Paul H. Netherwood, Jr.  
Lynn Seaman

January 1983



**US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND**  
**BALLISTIC RESEARCH LABORATORY**  
**ABERDEEN PROVING GROUND, MARYLAND**

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established how  $\sigma_{no}$  depends on the yield strength of the material and, second, an equation was developed that describes how the crack nucleation rate changes with stress. This relation applies for the entire range of stresses extending from the stress at which cracking begins to at least two and a half times this value.

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## 1. INTRODUCTION

Two previous determinations of the crack nucleation threshold stress  $\sigma_{no}$  in a low-alloy Ni-Cr steel led to values differing by a factor of 3.4.<sup>1,2</sup> The present study was initiated to clarify this situation by examining the nucleation process in more detail -- especially through investigations of cracking at stress levels near the threshold stress and as a function of the strength, or extent of tempering, of the steel.

## II. PROCEDURE

The material investigated was a low-alloy 0.22C-3Ni-1Cr tempered martensitic steel, and  $\sigma_{no}$  determinations were completed for three different rolling and tempering conditions. These corresponded to Brinell hardnesses of 270, 320, and 370 and yield strengths  $\sigma_Y$  of 0.65, 0.80 and 1.02 GPa, respectively.

Partially broken samples were created for investigation with parallel-plate impacts (plate-slap tests) accomplished with a light-gas gun. The degree of damage in the samples was varied by changing the impact velocity. In all tests of a particular material condition, identical impactor and sample thicknesses were used to insure approximately the same load duration.

Crack densities were established with microscopic observations of metallographically prepared sections of the partially broken samples.<sup>3</sup> In the plate-impact test, the load duration depends on the location in the plate. Hence, only voids in the central region -- a strip 0.021 to 0.127 cm wide -- of each sample were counted. This insured that voids in the regions investigated were initiated over approximately equal time intervals. It also allowed the use of data from the low-pressure tests where no noticeable cracking occurred in the outer regions of the plates.

The nucleation threshold stress was determined iteratively by first estimating an approximate threshold stress  $\sigma'_{no}$  by extrapolating curves of crack density versus the maximum compressive stress to the stress corresponding to no cracking. If this resulted in a stress less than the Hugoniot elastic limit (HEL),  $\sigma'_{no}$  was approximated with the HEL. Subsequently, the maximum tensile stress attained in each test was computed with the one-dimensional

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<sup>1</sup>L. D. Bertholf, L. D. Buxton, B. J. Thorne, R. K. Byers, A. L. Stevens, and S. L. Thompson, "Damage in Steel Plates from Hypervelocity Impact. II. Numerical Results and Spall Measurement," *J. Applied Phys.* **46**, 1975, pp 3776-3783.

<sup>2</sup>D. A. Shockey, L. Seaman, D. R. Curran, P. S. DeCarli, M. Austin and J. P. Wilhelm, "A Computational Model for Fragmentation of Armor Under Ballistic Impact," *Ballistic Research Laboratory Contract Report No. 222*, April 1975 (U).

<sup>3</sup>G. L. Moss, L. Seaman, "Nucleation Threshold Stress for the Dynamic Fracture of a Low-Alloy Ni-Cr Steel," *Mechanics of Materials*, **1**, 1982, pp 87-95.

stress wave-propagation computer code PUFF<sup>4</sup> with the brittle-fracture subroutine BFRAC<sup>4</sup>, and by using  $\sigma'_{no}$  and related material fracture parameters from independent tests<sup>2</sup>. Such a computation automatically accounts for the elastic-plastic wave interactions as well as the effect of void development on the intensity of the tensile stresses computed. Finally,  $\sigma_{no}$  was determined by extrapolating curves of crack density versus the maximum tensile stress to the tensile stress corresponding to no cracking. The stress at no cracking was assumed to be  $\sigma_{no}$ .

Crack morphology was examined at each strength level to aid in interpreting the results of the threshold determinations.

### III. RESULTS

Microscopic observations revealed that failure invariably started at inclusions which either cracked or separated from the matrix. Eventually, cracks extended from these regions into the matrix. Clearly, there are several distinct stages in the failure process, and nucleation can be described in several ways. Here, nucleation was associated with the beginning of the crack extensions into the steel matrix.

Graphs of the crack densities versus stress are shown in Figure 1 for the thermomechanical treatments corresponding to yield stresses of 0.65 and 1.02 GPa. It can be seen that the curves based on the tensile and compressive

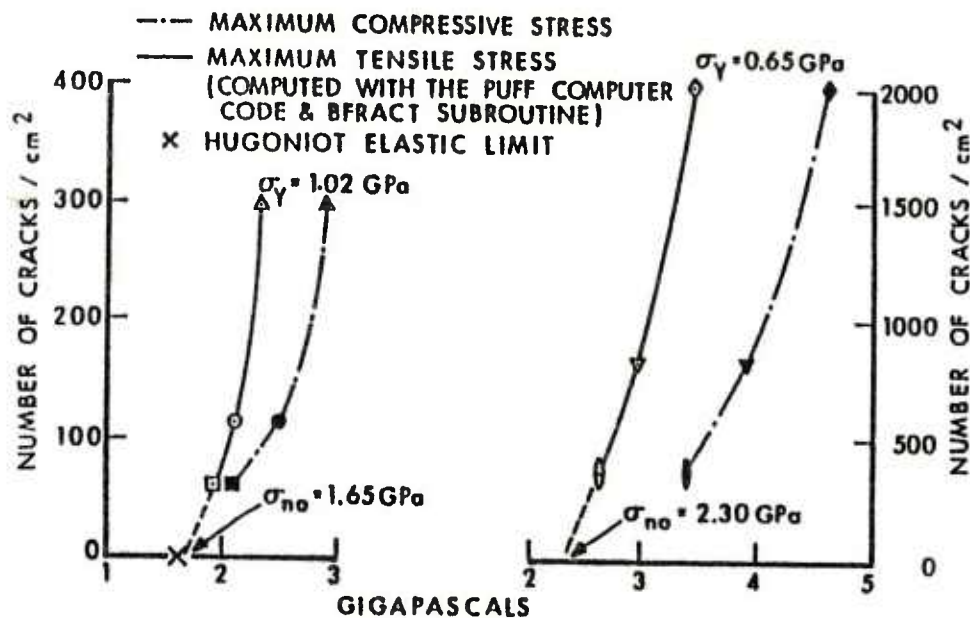


Figure 1. Crack density dependence on stress. Symbols with the same shape correspond to the same test.

<sup>4</sup>L. Seaman and D. R. Curran, "SRI PUFF 8 Computer Program for One-Dimensional Stress Wave Propagation," Ballistic Research Laboratory Contract Report No. 00420, March 1980 (U).



stresses do not extrapolate to the same no-damage levels. This is partly because there is insufficient cracking at stresses just above  $\sigma_{no}$  to get statistically significant crack densities. Since cracking is activated by tensile, rather than compressive, stresses,  $\sigma_{no}$  was related to the tensile stress at which cracking began. A new result shown in Figure 1 is that  $\sigma_{no}$  decreases as  $\sigma_Y$  increases over the stress range investigated.

The reason for this behavior is revealed by the appearance of the cracks. Examples are shown in Figures 2 and 3. It is readily seen in Figure 2 that when  $\sigma_Y$  equals 1.02 GPa, the cracks tend to extend along the edges of inclusions and appear as fine lines in the matrix. They are typical sharp cracks. In contrast, there is approximately spherical void growth around the inclusions in the lower strength steel ( $\sigma_Y = 0.65$  GPa) as shown in Figure 3. Eventually, matrix cracks form, but these are clearly nucleated with more plastic deformation than the cracks in the higher strength steel.

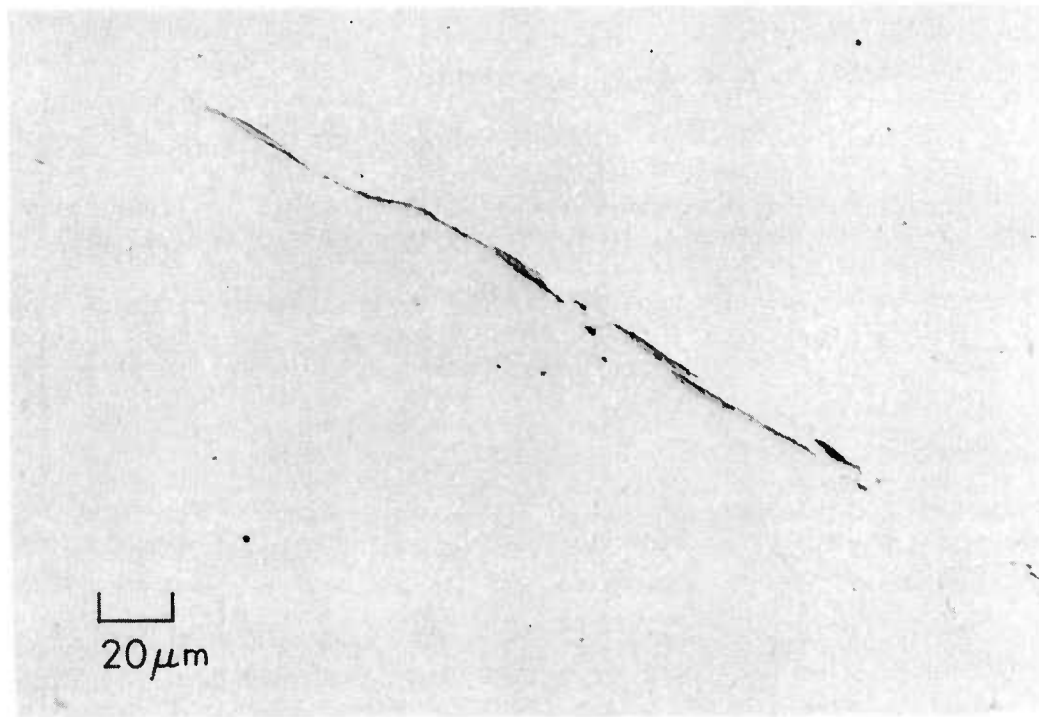


Figure 2. Sharp cracks at inclusion-matrix interfaces and in the steel matrix ( $\sigma_Y = 1.02$  GPa).



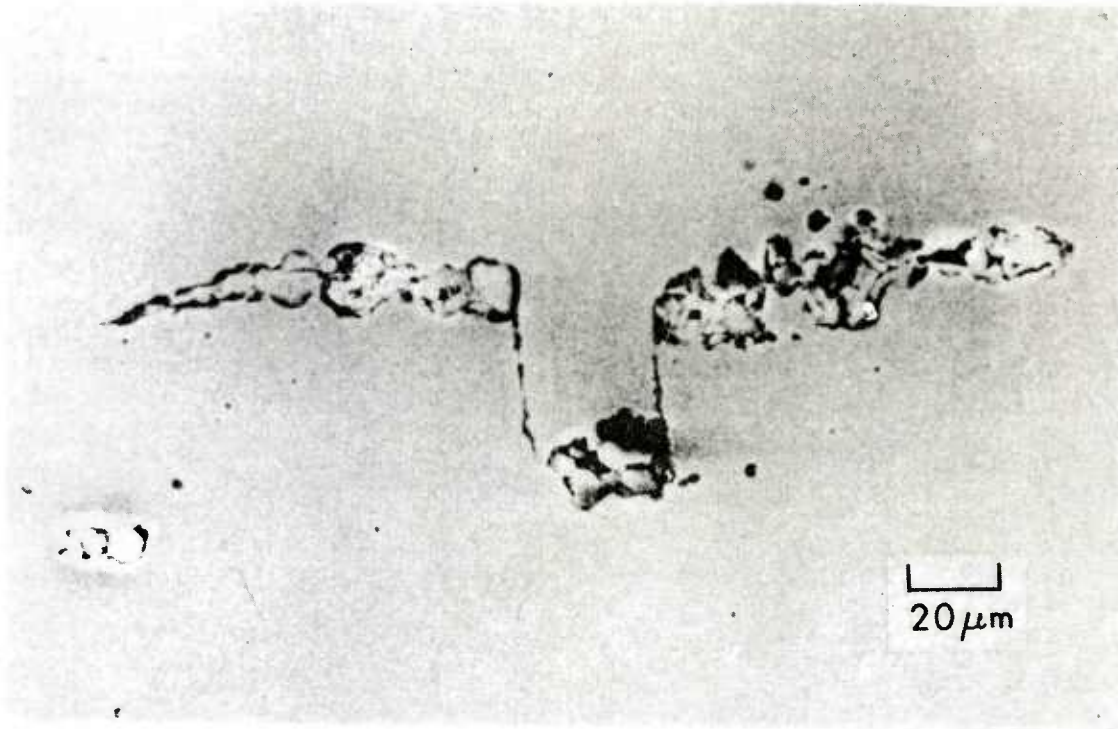


Figure 3. Approximately spherical void growth at inclusions.  
Vertical lines are shear cracks ( $\sigma_Y = 0.65$  GPa).

The nature of the cracking is further emphasized in Figure 4 where the data for the Ni-Cr steel and several other materials are shown along with curves that approximate bounding conditions for the development of failure.<sup>5-9</sup>

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<sup>5</sup>L. Seaman, T. W. Barbee, Jr. and D. R. Curran, "Dynamic Fracture Criteria of Homogeneous Materials," Air Force Weapons Laboratory Technical Report No. 71-156, February 1972 (U).

<sup>6</sup>D. A. Shockey, K. C. Dao and R. L. Jones, "Effect of Grain Size on the Static and Dynamic Fracture Behavior of  $\alpha$ -Titanium," Mechanisms of Deformation and Fracture, K. E. Easterling, Ed., Pergamon Press, Oxford, 1979, pp 77-85.

<sup>7</sup>D. R. Curran and D. A. Shockey, "Dynamic Fracture Criteria for Polycarbonate and Polyimide," Ballistic Research Laboratory Contract Report No. 91, March 1973 (U).

<sup>8</sup>L. Seaman and D. A. Shockey, "Models for Ductile and Brittle Fracture for Two-Dimensional Wave Propagation Calculations," Army Materials and Mechanics Research Center Contract Technical Report No. 75-2, February 1975.

<sup>9</sup>D. A. Shockey, L. Seaman and D. R. Curran, "Dynamic Fracture of Beryllium Under Plate Impact and Correlation with Electron Beam and Underground Test Results," Air Force Weapons Laboratory Technical Report No. 73-12, June 1973.

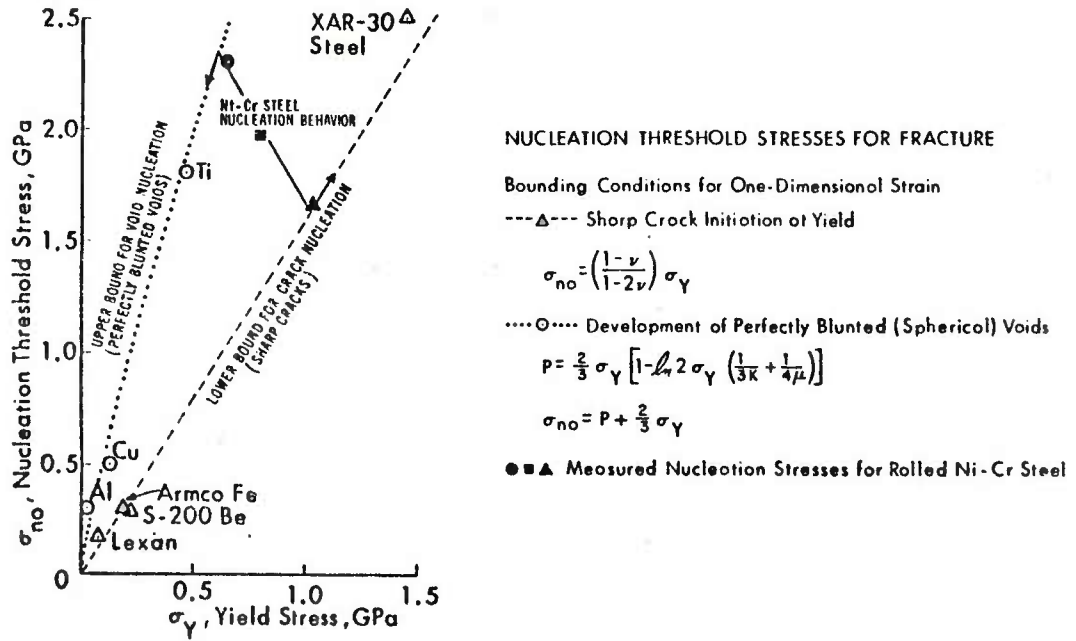


Figure 4. Nucleation threshold stresses for fracture with stress waves. The curves bounding the possible threshold stresses correspond to the development of perfectly sharp and perfectly blunted cracks.

The lower limit on threshold stresses for cracking was assumed to be the stress required to develop sharp cracks. This was approximated with the stress just sufficient to initiate plastic deformation. For plane-strain conditions, as encountered in the plate-impact test, the stress  $\sigma_{11}$  in the direction of wave propagation required to initiate plastic flow is proportional to the yield strength of the standard tensile test and is given by the relation

$$\sigma_{11} = (1-\nu)\sigma_Y/(1-2\nu). \quad (1)$$

This curve is shown in Figure 4 for a Poisson's ratio  $\nu$  of 0.27, and it is apparent that the threshold stresses for cracking in brittle materials in which sharp cracks form, i.e., Lexan, S-200 Be, Armco Fe and the Ni-Cr steel ( $\sigma_Y = 1.02$  GPa), almost coincide with this line. Hence, increasing  $\sigma_Y$  of the Ni-Cr steel above about 1 GPa should result in an increase in  $\sigma_{no}$ .

An upper bound on the stress to initiate cracks was assumed to be the stress to develop a perfectly blunted crack, i.e., a spherical pore. Hill has shown that the hydrostatic pressure  $P$  required to enlarge a spherical void in an infinite elastic-perfectly plastic solid is given by

$$P = (2\sigma_Y/3) \left\{ 1 - \ln \left[ 2\sigma_Y \left( \frac{1}{3K} + \frac{1}{4\mu} \right) \right] \right\}, \quad (2)$$

where  $K$  and  $\mu$  are the bulk and shear moduli, respectively.<sup>10</sup> The stress component  $\sigma_{11}$  in the direction the stress wave propagates is

$$\sigma_{11} = P + (2/3)\sigma_Y. \quad (3)$$

This is the stress component usually related to fracture with stress waves. When  $P$  is taken as the critical stress for void growth,  $\sigma_{11} = \sigma_{no}$ . This is plotted in Figure 4 for average values of  $K$  and  $\mu$  for ductile materials and is identified as the upper bound on  $\sigma_{no}$ . Measured threshold stresses for the nucleation of voids in ductile materials (Al, Cu, apparently Ti and the Ni-Cr steel when  $\sigma_Y = 0.65$  GPa) are also shown in Figure 4, and these are in close agreement with the upper limit for  $\sigma_{no}$ , i.e., the curve for perfectly blunted cracks. Since the critical condition for void growth is defined by the expression for  $P$ , the agreement between the data and the bounding curve is a quantitative indication that the initial approximately spherical void growth in ductile materials is governed by all the principal stress components rather than by  $\sigma_{11}$  alone.

It is apparent that there is a maximum in the  $\sigma_{no}$  vs.  $\sigma_Y$  curve for the Ni-Cr steel at about 0.6 GPa because the limiting curve for perfectly blunted cracks is an increasing function of yield stress while in the interval  $0.60 \leq \sigma_Y \leq 1.0$  GPa the threshold stress for cracking the Ni-Cr steel is a decreasing function of yield stress. This maximum should be an important feature in the design and selection of tempered martensitic steels that must resist fracture due to stress waves. The implication is that for some loads there may be a tempering condition that will result in optimum fracture resistance.

The data in Figure 1 are also helpful in establishing appropriate functions for the description of crack nucleation rates  $\dot{N}$ . Previous results have shown that at stresses appreciably greater than  $\sigma_{no}$ ,  $\dot{N}$  is approximately given by

$$\dot{N} = \dot{N}_0 \exp (\sigma_{11} - \sigma_{no}) / \sigma_1, \quad (4)$$

where  $\dot{N}_0$ ,  $\sigma_{no}$  and  $\sigma_1$  are material parameters. However, the graph shown in Figure 1 suggests the behavior of the high-strength steel ( $\sigma_Y = 1.02$  GPa) is actually consistent with<sup>3</sup>

$$\dot{N} = \dot{N}_0 \left\{ \exp [(\sigma_{11} - \sigma_{no}) / \sigma_1]^{1.25} - 1 \right\}. \quad (5)$$

Hence, when  $\sigma$  equals  $\sigma_{no}$ , the nucleation rate is zero and not  $\dot{N}_0$ . At stresses appreciably above  $\sigma_{no}$ , Eq. 1 and the relation for  $\dot{N}$  that has been used in the past are approximately the same.

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<sup>10</sup>R. Hill, *Plasticity*, Oxford University Press, Oxford, 1950, p 104.

#### IV. CONCLUSIONS

New features discovered about the fracture with stress waves of a quenched and tempered low-alloy 3Ni-1Cr steel are as follows:

1. At low stresses, the threshold stress  $\sigma_{no}$  for the nucleation of cracks with stress waves increases with increasing yield strength  $\sigma_Y$ . However, at approximately 0.65 GPa there is a maximum and at 1.02 GPa a minimum in the  $\sigma_{no}$ - $\sigma_Y$  curve. The quantitative dependence of  $\sigma_{no}$  on  $\sigma_Y$  is given by the following relations.

When  $\sigma_Y$  is within the stress interval  $\sigma^* \leq \sigma_Y \leq 0.65$  GPa with the lower bound  $\sigma^*$  being the lowest stress that will form a spherical void,

$$\sigma_{no} = \frac{4}{3} \sigma_Y \left[ 1 - \frac{1}{2} \ln 2\sigma_Y \left( \frac{1}{3K} + \frac{1}{4\mu} \right) \right].$$

When  $0.65 \leq \sigma_Y \leq 1.02$  GPa,

$$\sigma_{no} = -1.71 \sigma_Y + 3.38.$$

When  $\sigma_Y \geq 1.02$  GPa,

$$\sigma_{no} = (1 - \nu) \sigma_Y / (1 - 2\nu).$$

The stress corresponding to the lower bound  $\sigma^*$  is unknown, but crack blunting should not be expected behavior for indefinitely low values of  $\sigma_Y$ . Sharp cracks should be encountered when there is massive ferrite since ferrite is known to cleave. This condition should define  $\sigma^*$ .

2. Intermediate behavior in which  $\sigma_{no}$  decreases as  $\sigma_Y$  increases corresponds to a decrease in the degree of plastic blunting at crack tips as the yield strength increases.

3. The nucleation rate at stresses near  $\sigma_{no}$  is given by

$$\dot{N} = \dot{N}_0 \left\{ \exp [(\sigma_{11} - \sigma_{no})/\sigma_1]^{1.25} - 1 \right\}$$

when  $\sigma_Y = 1.02$  GPa. The above relation reflects a significant improvement in our understanding of the rate at which cracks nucleate at low stresses -- stresses in the vicinity of  $\sigma_{no}$ , and it should allow better quantitative predictions of the damage due to fracture with stress waves.

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